

Green Process Innovation Strategies and Environmental Sustainability among Manufacturing Firms: The Mediating Role of Green Supply Chain Management

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ABSTRACT

Environmental sustainability has become a critical concern for manufacturing firms due to increasing pressure to reduce carbon emissions, industrial waste, and inefficient resource utilization. In Kenya's South Rift region, manufacturing industries play a significant role in economic development but continue to contribute substantially to environmental degradation. Despite growing regulatory requirements and stakeholder expectations, empirical evidence on how green process innovation enhances environmental sustainability remains limited, particularly regarding the role of green supply chain management. This study examined the mediating effect of green supply chain management on the relationship between green process innovation and environmental sustainability among manufacturing firms in the South Rift region of Kenya. Guided by Innovation Theory of Diffusion. The study adopted a positivist philosophy and a cross-sectional causal research design. Data were collected using structured questionnaires from 162 senior managers drawn from 81 registered manufacturing firms. The data were analyzed using Partial Least Squares Structural Equation Modelling (PLS-SEM). The findings indicate that green process innovation significantly improves environmental sustainability through enhanced resource efficiency, waste reduction, and emission control. Furthermore, green supply chain management significantly strengthens the relationship between green process innovation and environmental sustainability ($\beta = 0.224, p < 0.05$), suggesting that cleaner production technologies generate stronger environmental outcomes when integrated with environmentally responsible procurement, manufacturing, and logistics practices. The study concludes that manufacturing firms can achieve superior environmental performance by aligning internal green process innovations with supply chain sustainability initiatives. The study recommends that managers invest in cleaner production technologies and integrate green supply chain practices to accelerate sustainable industrial development.

Key Words: Green Process Innovation Strategy, Environmental Sustainability, Diffusion Theory of Innovation, Kenya.

INTRODUCTION

Environmental sustainability has become a critical global priority due to escalating climate change, environmental degradation, and resource depletion associated with industrialization and economic growth. Since the Industrial Revolution, manufacturing activities have substantially contributed to greenhouse gas emissions, resource overconsumption, waste generation, and environmental pollution (Alkaraan, Albitar, Hussainey, & Venkatesh, 2022). Consequently, governments, international organizations, and businesses have increasingly embraced green growth initiatives and sustainable development strategies aimed at reducing environmental impacts while maintaining economic competitiveness (Abbas & Dogan, 2022).

The global transition toward cleaner production systems align with the Sustainable Development Goals (SDGs), particularly those promoting responsible consumption and production, climate action, and sustainable

industrialization. These goals emphasize waste reduction, resource efficiency, pollution control, and recycling as essential mechanisms for achieving long-term environmental sustainability (UNDP, 2021). Within this context, green innovation has emerged as a strategic approach through which organizations can improve environmental performance while enhancing operational efficiency and competitive advantage.

Green innovation refers to the development and implementation of environmentally friendly products, processes, technologies, and managerial practices that minimize ecological harm and promote sustainable development (Polas, Tabash, Bhattacharjee, & Dávila, 2023). Among the various dimensions of green innovation, green process innovation has attracted considerable scholarly attention because of its direct influence on manufacturing operations and environmental outcomes.

Green process innovation involves the adoption of cleaner production technologies, eco-efficient manufacturing techniques, waste minimization systems, energy-efficient processes, and pollution prevention mechanisms designed to reduce the environmental footprint of production activities (Khan, Kaur, Jabeen, & Dhir, 2021). Through environmental science and technology, organizations can redesign production processes to improve resource utilization, lower carbon emissions, and minimize waste generation, thereby enhancing environmental sustainability (Lv, Shao, & Lee, 2021; Rehman et al., 2021).

Globally, manufacturing firms have increasingly integrated green process innovation into their operations in response to regulatory requirements, stakeholder expectations, and market demand for environmentally responsible products. In the United States, firms have adopted eco-friendly technologies and cleaner production systems to reduce environmental impacts while improving competitiveness (Jahanger et al., 2023). Similarly, evidence from Latin America indicates that firms investing in green innovation strategies achieve competitive advantages as consumers increasingly favor environmentally conscious brands (Dos-Santos-Dalbelo & Rutkowski, 2021).

European manufacturing firms remain at the forefront of green industrial transformation due to stringent environmental regulations and strong institutional support. The European Union has incentivized organizations to adopt green technologies and resource-efficient production processes aimed at reducing emissions and improving environmental performance (Raza, 2020). Empirical evidence indicates that green innovation and sustainable supply chain practices are widely implemented across European manufacturing industries, contributing to enhanced environmental sustainability through improved resource efficiency and reduced pollution levels (Cainelli, D'Amato, & Mazzanti, 2020).

In Asia, countries such as China and Japan have intensified efforts to promote cleaner production systems in response to growing concerns over resource scarcity and environmental degradation (Shahab et al., 2020). Chinese manufacturing firms have increasingly adopted cleaner technologies and environmentally sustainable production processes to address air pollution and carbon emissions (Qiu, Jie, Wang, & Zhao, 2020). Similarly, Malaysian manufacturing firms have embraced green management practices to reduce their carbon footprint and improve sustainability performance (Nisar et al., 2021).

Despite growing global interest in green process innovation, its adoption across Africa remains uneven due to infrastructural limitations, inadequate access to green technologies, financial constraints, and weak regulatory enforcement (Amankwah-Amoah, 2019). Evidence from Nigeria suggests that green innovation practices are more prevalent among large firms and multinational corporations, while small and medium-sized enterprises often struggle to invest in sustainable technologies (Agyabeng-Mensah, Afum, & Baah, 2022). Likewise, firms in Ghana continue to experience challenges in implementing environmentally sustainable supply chain and production practices (Antwi, Agyapong, & Owusu, 2022).

In Kenya, environmental sustainability has become a strategic policy priority under the Kenya Vision 2030 agenda and the Climate Change Act of 2016, both of which advocate for low-carbon development and sustainable industrialization (Mukabi, 2023). Although the manufacturing sector contributes significantly to national economic growth and employment, it remains a major source of carbon emissions, industrial waste, and water pollution (Kwakwa, 2026). Regulatory agencies, including the National Environment Management Authority (NEMA), have established environmental compliance frameworks; however, enforcement challenges and limited

adoption of integrated green practices continue to constrain progress toward sustainable manufacturing (Lema, 2025).

The South Rift region, comprising Bomet, Kericho, Nakuru, Narok, Baringo, and Samburu counties, hosts diverse manufacturing industries, including tea processing factories, agro-processing plants, cement manufacturers, steel industries, and plastic production firms. While these industries contribute substantially to regional economic development and employment creation, their operations generate significant environmental externalities, including carbon emissions, industrial effluents, air pollution, and solid waste (Albertazzi, Bini, & Trivellini, 2023). The region surrounds the Mau Forest ecosystem, Kenya's largest water catchment area, making environmental sustainability particularly critical.

The South Rift region has also experienced increasing climate-related challenges, including rising temperatures, prolonged droughts, flooding, and food insecurity (Njenga, 2021). Manufacturing activities that rely heavily on fossil fuels, inefficient technologies, and unsustainable production processes further exacerbate these environmental challenges (Tanveer, Song, Faheem, Daud, & Naseer, 2021). Consequently, there is an urgent need for manufacturing firms to adopt green process innovation strategies that enhance resource efficiency while minimizing environmental degradation.

The effectiveness of green process innovation may depend on complementary organizational capabilities, particularly green supply chain management (GSCM). Green supply chain management integrates environmental considerations into sourcing, production, logistics, distribution, and reverse logistics activities to improve sustainability outcomes (Yun, Shun, Jackson, Newiduum, & Browndi, 2023). Green procurement, green manufacturing, green logistics, and green distribution practices enable firms to extend environmental responsibility beyond internal operations to encompass the entire value chain (Kipruto & Shale, 2018; Rauf et al., 2022; Feng et al., 2017; Khan et al., 2021).

Existing evidence suggests that green supply chain practices strengthen firms' ability to translate environmental initiatives into measurable sustainability outcomes by enhancing resource efficiency, reducing waste, minimizing emissions, and improving compliance with environmental regulations (Novitasari & Agustia, 2021; Hashmi & Akram, 2021). Therefore, green supply chain management may serve as an important mediating mechanism that influences the effectiveness of green process innovation in improving environmental sustainability.

Environmental sustainability refers to organizational efforts aimed at preserving natural resources, reducing ecological degradation, and ensuring long-term environmental well-being through efficient resource utilization and responsible production practices (Ullah, Ahmad, & Rehman, 2021). In manufacturing contexts, environmental sustainability is commonly reflected through improvements in energy efficiency, water conservation, waste reduction, material efficiency, greenhouse gas emission reduction, toxic chemical management, and environmental compliance (Wang, Abbas, Sial, Alvarez-Otero, & Cioca, 2022).

Although prior studies have established the importance of green process innovation in enhancing firm performance, most have concentrated on financial and operational outcomes while paying limited attention to direct environmental benefits. For example, Xie, Huo, and Zou (2019) examined the financial implications of green process innovation without explicitly assessing environmental outcomes. Similarly, Xie, Hoang, and Zhu (2022) investigated the relationship between green process innovation and financial performance while overlooking its effects on carbon reduction and environmental sustainability. Other studies have focused primarily on organizational success indicators rather than environmental impacts (Jirapol, Yuosre, & Bjorn, 2021; Sedianingsih, 2018).

Furthermore, existing literature provides limited empirical evidence regarding the interaction between green process innovation and green supply chain management in influencing environmental sustainability, particularly within developing economies. In Kenya, and specifically in the South Rift region, research examining how green supply chain practices condition the effectiveness of green process innovation remains scarce. This contextual and theoretical gap limits understanding of how manufacturing firms can strategically integrate internal process innovations with environmentally sustainable supply chain practices to achieve superior environmental outcomes.

Accordingly, this study seeks to examine the mediating effect of green supply chain management on the relationship between green process innovation and environmental sustainability among manufacturing firms in the South Rift region of Kenya.

LITERATURE REVIEW

Green Processing and Sustainable Environmental

Green process innovation refers to the modification or redesign of production processes to reduce environmental harm through improved resource efficiency, waste minimization, energy conservation, and emission control. It involves the adoption of eco-friendly technologies, sustainable resource utilization, and pollution control mechanisms (Khan, Kaur, Jabeen, & Dhir, 2021). Several studies have explored the impact of green process innovation on corporate financial performance and sustainability, yet gaps remain in understanding its direct influence on environmental sustainability, particularly in high-pollution industries such as manufacturing.

Globally, Xie, Huo, and Zou (2019) examined the relationship between green process innovation, green product innovation, and corporate financial performance. Using content analysis on data from 209 listed firms in pollution-intensive industrial sectors, the study found that green process innovation positively influences both financial performance and green product innovation. However, while financial benefits were highlighted, the study did not explicitly analyze the environmental performance outcomes of green process innovation. The present study addresses this gap by focusing on how green process innovation directly impacts environmental sustainability.

Xie, Hoang, and Zhu (2022) investigated the link between green process innovation and financial performance, emphasizing the moderating effects of green social capital and consumer-driven green requirements. Based on survey data from 221 Chinese manufacturing firms, the study revealed a U-shaped relationship, where initial green process innovation investments negatively impact financial performance before yielding long-term benefits. Additionally, green social capital mitigates the adverse effects, while green requirement strategies enhance the benefits. However, the study did not assess environmental outcomes such as carbon footprint reduction and energy efficiency improvements. The current study bridged this gap by examining green process innovation's direct role in improving environmental sustainability.

Jirapol, Yuosre, and Bjorn (2021) assessed the efficiency of translating green strategic intent into green process innovation performance. Using the theories of green intellectual capital and complementary assets, they developed a model to explain how companies implement green process innovations. Regression analysis of multi-source survey data from 514 managers in 257 firms found that green strategic intent positively influences human, organizational, and relational aspects of green intellectual capital, all of which enhance green process innovation performance. However, the study focused on strategic intent rather than actual environmental impact. This study extended the literature by evaluating whether green process innovation effectively leads to tangible environmental performance improvements.

In Indonesia, Sedianingsih (2018) analyzed the impact of green process and product innovation on firm success using data from 125 manufacturing firms listed on the Indonesian Stock Exchange. Multiple linear regression results showed that green process innovation had a significant positive impact on company performance, while green product innovation had a negative but statistically insignificant effect. Despite these insights, the study focused on financial rather than environmental performance. The current study addressed this gap by linking green process innovation to environmental sustainability outcomes, such as waste reduction, emission control, and resource conservation.

Green Process Innovation, Green Supply Chain Management and Sustainable Environment

Green supply chain management (GSCM) has emerged as a strategic capability that enables organizations to integrate environmental considerations into procurement, manufacturing, logistics, distribution, and reverse logistics activities to enhance sustainability outcomes. Although previous studies have established positive

associations between green innovation and environmental performance, limited attention has been devoted to understanding whether GSCM strengthens the effectiveness of green process innovation in improving environmental sustainability.

Feng et al. (2017) investigated the relationship between GSCM, operational performance, environmental performance, and financial outcomes among 126 automotive firms in China using structural equation modelling. The findings revealed that GSCM significantly improved environmental performance through enhanced operational capabilities. Although the study did not explicitly test a mediating effect, it demonstrated that supply chain practices complement internal environmental initiatives in generating superior sustainability outcomes. However, the study emphasized financial performance and did not isolate green process innovation as a predictor of environmental sustainability.

Khan, Ajmal, Jabeen, and Talwar (2021) conceptualized GSCM from a resource-based perspective using data from 381 manufacturing firms in the United Kingdom. Their findings highlighted that supply chain connectivity, information sharing, and top management commitment enhance the effectiveness of environmental initiatives. While the study did not examine moderation effects, it suggested that GSCM functions as an organizational capability that facilitates the translation of green innovations into improved environmental outcomes. Nevertheless, the relationship between green process innovation and environmental sustainability was not empirically assessed.

Rauf et al. (2022) examined the relationship between GSCM practices, technological innovation, and operational performance among Pakistani manufacturing firms using Partial Least Squares Structural Equation Modelling (PLS-SEM). The results indicated that GSCM enhances technological innovation and operational efficiency. Although environmental sustainability was not included as an outcome variable, the study provides empirical support for the complementary role of GSCM in strengthening the effectiveness of innovation practices. However, the authors did not investigate whether GSCM moderates the influence of green process innovation on environmental outcomes.

Fianko et al. (2021) analyzed the effects of internal and external green supply chain practices on environmental performance within the construction industry. Using structural equation modelling, the study found that green purchasing and green construction positively influenced environmental performance. The findings suggest that supply chain practices enhance the environmental benefits of organizational sustainability initiatives. However, the study focused exclusively on direct effects and did not examine the interaction between green process innovation and GSCM.

Similarly, Mamun et al. (2021) assessed the influence of GSCM practices on environmental performance in manufacturing firms in Bangladesh. Their findings indicated that green purchasing significantly improves environmental performance, while other supply chain practices exhibit mixed effects. Although the study underscores the importance of GSCM in achieving sustainability objectives, it did not investigate the extent to which GSCM conditions the effectiveness of green process innovation.

Within the African context, Bolaji, Rahim, and Omar (2022) examined the relationship between GSCM and organizational performance among manufacturing firms in Nigeria. The study established that internal GSCM processes positively influence environmental performance. However, the authors did not evaluate the interaction effects between green innovation strategies and GSCM, leaving unanswered questions regarding the contingent role of supply chain practices in enhancing environmental sustainability.

In Kenya, Ochieng (2019) investigated green supply chain practices among chemical manufacturing firms and found that green procurement significantly improved firm performance. Likewise, Eshikumo and Odock (2017) established a positive relationship between green manufacturing practices and operational performance within Kenya's cement industry. However, both studies focused on performance outcomes rather than environmental sustainability and did not examine whether GSCM moderates the relationship between green process innovation and environmental sustainability.

The existing studies provide substantial evidence that both green process innovation and GSCM independently contribute to improved environmental outcomes. However, empirical research examining GSCM as a mediating variable in the relationship between green process innovation and environmental sustainability remains scarce, particularly in developing economies. Furthermore, no known study has investigated this relationship among manufacturing firms in Kenya's South Rift region. This conceptual, contextual, and geographical gap justifies the current study, which examines whether GSCM strengthens the effect of green process innovation on environmental sustainability.

Theoretical Review

The Diffusion of Innovation (DOI) Theory, developed by Rogers in 1962, explains how innovations are communicated and adopted over time within a social system. The theory posits that the diffusion process follows a predictable pattern comprising innovators, early adopters, early majority, late majority, and laggards (Godin, 2019). According to the theory, the adoption of an innovation depends on its perceived characteristics, including relative advantage, compatibility, complexity, trialability, and observability. Communication channels, organizational structures, and external environmental pressures also influence the rate and extent of innovation diffusion.

Diffusion of Innovation Theory provides a useful framework for understanding the adoption and implementation of green process innovation within manufacturing firms. Green process innovation involves the introduction of cleaner production technologies, energy-efficient manufacturing systems, waste minimization practices, and pollution prevention mechanisms aimed at reducing environmental impacts (Khan, Kaur, Jabeen, & Dhir, 2021). The theory suggests that firms are more likely to adopt green process innovations when they perceive clear environmental and economic benefits, possess adequate technological capabilities, and operate within supportive institutional environments.

Recent studies have applied Diffusion of Innovation Theory to explain the adoption of environmentally sustainable technologies and practices. Huang et al. (2022) argue that technological innovation plays a critical role in addressing environmental challenges and advancing sustainability objectives. Similarly, Shahzad, Qu, Rehman, and Zafar (2022) contend that the development and diffusion of environmentally friendly technologies are essential for achieving sustainable development goals. Bett (2024) further emphasizes that green innovation strategies are increasingly diffused across industries as organizations respond to stakeholder expectations, environmental regulations, and competitive pressures.

Within the context of this study, green supply chain management (GSCM) is conceptualized as an organizational capability that enhances the effectiveness of green process innovation. While green process innovation focuses on improving internal production processes, GSCM extends environmental considerations across procurement, manufacturing, logistics, distribution, and reverse logistics activities. The integration of green supply chain practices facilitates the diffusion and implementation of green process innovations throughout the value chain, thereby strengthening their contribution to environmental sustainability.

Although previous studies have linked green innovation to sustainable development, financial performance, and environmental performance (Ullah, Ahmad, & Rehman, 2021; Wang et al., 2022; Khan et al., 2023; Su et al., 2020), limited research has examined how green supply chain management conditions the relationship between green process innovation and environmental sustainability. Existing GSCM studies have largely focused on direct effects on operational or financial outcomes rather than its contingent role in enhancing the environmental benefits of green process innovation (Feng et al., 2017; Akhtar, 2019; Bolaji, Rahim, & Omar, 2022; Yassine, 2022).

Furthermore, most empirical studies have been conducted among small and medium-sized enterprises, high-technology firms, or manufacturing firms in developed and emerging economies such as China, Indonesia, and Pakistan (Singh et al., 2020; Dzikriansyah et al., 2023). Evidence from manufacturing firms in developing countries, particularly Kenya, remains limited. In addition, prior studies have predominantly employed regression

analysis and general survey designs, with relatively few applying Partial Least Squares Structural Equation Modelling (PLS-SEM) to investigate moderation effects.

Therefore, Diffusion of Innovation Theory provides a suitable theoretical lens for explaining how green process innovations are adopted and diffused within manufacturing firms and how green supply chain management strengthens the translation of these innovations into improved environmental sustainability outcomes. The theory supports the proposition that firms integrating green process innovation with sustainable supply chain practices are more likely to achieve superior environmental performance through reduced emissions, enhanced resource efficiency, and effective waste management.

RESEARCH METHODOLOGY

This study was anchored on the positivist research philosophy, which emphasizes objective measurement, empirical observation, and statistical testing of hypothesized relationships among variables (McGlinchey, 2022). A causal research design incorporating correlational and cross-sectional approaches was adopted to examine the mediating effect of green supply chain management on the relationship between green process innovation and environmental sustainability. The study was conducted among manufacturing firms operating in the South Rift region of Kenya, comprising Baringo, Bomet, Kericho, Nakuru, Narok, and Samburu counties. The region hosts diverse manufacturing subsectors, including tea, coffee, dairy, cement, steel, plastics, textiles, pharmaceuticals, and construction materials, whose operations have significant implications for environmental sustainability.

The target population comprised 81 registered manufacturing firms operating within the South Rift region. Given the manageable population size, a census approach was adopted, whereby all firms were included in the study. Two senior managers from each firm, specifically general managers and operations managers, were purposively selected as key respondents because of their strategic involvement in environmental management, production processes, and supply chain decision-making, resulting in a target sample of 162 respondents. Quantitative data were collected using a structured questionnaire administered through both online and physical modes to improve accessibility and response rates. The questionnaire measured green process innovation, green supply chain management, and environmental sustainability using validated multi-item scales adapted from previous studies. To enhance instrument quality, a pilot study involving 20 respondents from Litein Tea Factory was conducted, yielding Cronbach's alpha coefficients exceeding the recommended threshold of 0.70 for all constructs.

Data were analyzed using the Statistical Package for the Social Sciences (SPSS) version 27.0 and SmartPLS 4 software. Descriptive statistics, including means and standard deviations, were generated to summarize the study variables, while Partial Least Squares Structural Equation Modelling (PLS-SEM) was employed to test the hypothesized relationships. The measurement model was assessed using indicator loadings, composite reliability, average variance extracted (AVE), the Fornell-Larcker criterion, and the heterotrait-monotrait ratio (HTMT) to which establish the instrument was reliability and validity. The mediating effect of green supply chain management on the relationship between green process innovation and environmental sustainability was examined through interaction-term analysis using a bootstrapping procedure with 5,000 resamples at a 95% confidence level. Ethical approval was obtained from the University of Kabianga and the National Commission for Science, Technology and Innovation (NACOSTI), while informed consent, confidentiality, and voluntary participation were upheld throughout the study.

RESULTS AND DISCUSSION

Descriptive Results

Manufacturing firms in the South Rift region reported high adoption of both green process innovation and green supply chain management practices, indicating that environmental sustainability has become an integral component of their operational and strategic activities. Green process innovation recorded a high overall mean of 3.89 (SD = 0.69), demonstrating that firms have integrated environmentally friendly production practices into their operations. The strongest areas of implementation were ICT adoption, the introduction of green manufacturing processes, and process restructuring to reduce pollution and resource wastage, while

improvements in energy efficiency and raw material handling were also widely adopted. However, the relatively lower rating for fossil fuel reduction indicates that deep decarbonization initiatives remain constrained by technological and financial limitations.

Similarly, green supply chain management recorded a high overall mean of 3.92 (SD = 0.69), reflecting widespread integration of environmental sustainability across procurement, manufacturing, and logistics functions. Green procurement emerged as the most developed dimension, characterized by the sourcing of environmentally friendly materials and collaboration with environmentally compliant suppliers, followed by green manufacturing practices such as modern production technologies and lean manufacturing. Although firms had also embraced green logistics through route optimization and reverse logistics, the adoption of low-carbon transport and machinery remained comparatively weaker. Overall, the findings suggest that while manufacturing firms have institutionalized sustainable production and supply chain practices, further investments are needed to accelerate decarbonization and strengthen environmentally sustainable logistics operations.

Mediation Effects Model Results

The first-order structural model results estimated using SmartPLS to examine the mediating role of Green Supply Chain Management (GSCM) in the relationship between Green process innovation and Environmental Sustainability. The direct relationship between variable are given by the following.

Table 1

Direct Effects of First-Order Structural Model

	Original sample (β)	Sample mean (M)	Standard deviation (STDEV)	T statistics ($ O/STDEV $)	P values
Green Process Innovation -> Environmental Sustainability	0.245	0.248	0.087	2.810	0.005
Green Process Innovation -> Green Supply Chain	0.419	0.413	0.117	3.586	0.000
Green Supply Chain -> Environmental Sustainability	0.534	0.531	0.129	4.154	0.000

Source: Field Questionnaire Results (2026)

The results indicate that Green Process Innovation has a statistically significant positive effect on Environmental Sustainability ($\beta = 0.245$, $t = 2.810$, $p = 0.005$). This confirms that process innovation directly enhances environmental outcomes, implying that firms' process-level efficiencies and cleaner production systems contribute meaningfully to sustainability performance. Consequently, the direct effect supports a rejection of the null hypothesis for this pathway at the direct level.

There existed also statistically positive significant relationship between green process innovation and green supply chain ($\beta = 0.245$, $t = 2.810$, $p = 0.005$). It there shows that the exist a relation to green supply chain management. The strongest relationship observed is between Green Supply Chain Management and Environmental Sustainability ($\beta = 0.534$, $t = 4.154$, $p = 0.000$). This confirms that GSCM is a dominant predictor of environmental performance, reinforcing its theoretical role as a central coordinating mechanism that translates innovation practices into environmental outcomes.

The implication is that the direct effects confirm that process innovation directly enhance environmental sustainability.

Table 2

Indirect Effects of First-Order Structural Model

	Original sample (β)	Sample mean (M)	Standard deviation (STDEV)	T statistics ($ O/STDEV $)	P values
Green Process Innovation $\rightarrow$ Green Supply Chain $\rightarrow$ Environmental Sustainability	0.224	0.221	0.086	2.612	0.009

Source: Field Questionnaire Results (2026)

The results show that Green Process Innovation $\rightarrow$ GSCM $\rightarrow$ Environmental Sustainability is statistically significant ($\beta = 0.224$, $t = 2.612$, $p = 0.009$). This indicates that GSCM partially mediates the relationship, meaning process innovation enhances sustainability both directly and indirectly through supply chain integration. This provides strong empirical evidence that supply chain mechanisms amplify the environmental impact of process innovations.

Summary of Hypotheses Testing

H_0 : Green Process Innovation $\rightarrow$ Green Supply Chain $\rightarrow$ Environmental Sustainability

Hypothesis H_{01} stated that *there is no statistically significant mediating effect of green supply chain management on the relationship between green process innovation strategy and environmental sustainability among manufacturing firms*. The first-order mediation results show a significant indirect effect ($\beta = 0.224$, $p = 0.009$), which is below the 0.05 threshold.

Based on the decision rule ($p < 0.05$), the null hypothesis is rejected. This confirms that green supply chain management significantly mediates the relationship between green process innovation and environmental sustainability. The implication is that process-oriented green innovations only translate into sustainability outcomes when effectively embedded within supply chain systems. This strengthens the first-order mediation pathway and confirms its statistical robustness.

Discussion of Findings

Null Hypothesis H_0 stated that there is no statistically significant mediating effect of green supply chain management on the relationship between green process innovation strategy and environmental sustainability among manufacturing firms. The first-order structural model produced a statistically significant indirect effect ($\beta = 0.224$, $p = 0.009$), which is below the 0.05 significance threshold. Based on the decision criterion of $p < 0.05$, the null hypothesis was rejected. The findings therefore confirm that green supply chain management significantly mediates the relationship between green process innovation and environmental sustainability. This suggests that improvements in cleaner production processes, efficient resource utilization, waste minimization, and energy-saving technologies contribute more strongly to environmental sustainability when they are integrated into broader supply chain practices such as green procurement, green manufacturing, and environmentally responsible logistics. In substantive terms, the results indicate that process-level green innovations alone may not fully generate sustainability gains unless they are operationalized through supply chain systems that extend environmental responsibility across the value chain.

The findings of this study are consistent with prior empirical literature. For instance, Xie, Huo, and Zou (2019) found that green process innovation positively influenced firm performance and green product innovation among pollution-intensive firms. Although their study emphasized financial outcomes rather than environmental sustainability, the present findings extend this evidence by demonstrating that green process innovation also generates significant environmental outcomes when mediated by green supply chain management. Similarly, Xie, Hoang, and Zhu (2022) reported that green process innovation yields long-term performance benefits, although

initial implementation costs may temporarily constrain returns. Their study highlighted the importance of supportive organizational conditions. The current study complements this position by showing that green supply chain management provides an important organizational and operational mechanism through which green process innovation translates into measurable sustainability outcomes.

The results also concur with the work of Jirapol, Yuosre, and Bjorn (2021), who found that green strategic intent enhances green process innovation capability through green intellectual capital. However, their analysis focused primarily on innovation capability rather than actual environmental outcomes. The present study advances this literature by empirically demonstrating that process innovation contributes to environmental sustainability through an identifiable mediating pathway. Likewise, the findings are broadly aligned with Sedianingsih (2018), who reported a significant positive effect of green process innovation on firm success in Indonesian manufacturing firms. While that study emphasized organizational performance, the current findings show that the benefits of green process innovation extend beyond financial and operational outcomes to environmental sustainability.

From the researcher's perspective, manufacturing firms should not treat green process innovation as an isolated internal production initiative. Rather, process innovation should be embedded within integrated green supply chain systems if firms are to realize stronger environmental benefits. Managers should therefore align factory-level process improvements with supplier environmental standards, cleaner production coordination, efficient material flows, and sustainable logistics practices. This implies that future environmental performance in manufacturing will increasingly depend not only on the adoption of green technologies within production processes, but also on the extent to which such innovations are institutionalized across the supply chain network.

CONCLUSIONS AND RECOMMENDATIONS

Summary Results

The structural results further demonstrated that green process innovation had a positive and statistically significant relationship with environmental sustainability. The direct effect confirmed that firms that adopted cleaner technologies, minimized waste, improved resource efficiency, and restructured production systems were more likely to report improved environmental outcomes. This finding suggests that green process innovation functions as an important internal operational capability through which firms reduce emissions, control pollution, and optimize resource utilization. The result therefore affirms that environmental sustainability is strengthened when environmental objectives are embedded directly within production and operational routines rather than treated merely as compliance obligations.

The mediation analysis provided additional insight into the mechanism through which green process innovation influences environmental sustainability. The indirect effect through green supply chain management was positive and statistically significant ($\beta = 0.224$, $p = 0.009 < 0.05$). This finding indicates that the environmental contribution of green process innovation becomes stronger when cleaner internal production systems are linked with environmentally responsible procurement, green manufacturing coordination, sustainable logistics, and efficient material flow management across the supply chain. In practical terms, the findings suggest that process-level environmental improvements alone may not fully maximize sustainability outcomes unless they are supported by integrated green supply chain practices that extend environmental responsibility across the broader value chain.

Conclusions

The study concludes that green process innovation is a key operational mechanism through which manufacturing firms enhance environmental sustainability. The adoption of cleaner production technologies, digitalized process systems, energy-efficient operations, and pollution control measures directly improves environmental performance by reducing waste, emissions, and resource consumption. However, the findings further demonstrate that the effectiveness of green process innovation is significantly strengthened when it is embedded within green supply chain management systems. This indicates that process-level environmental improvements are most

impactful when they extend beyond internal operations and are reinforced through coordinated procurement, production, and logistics practices across the supply chain.

Recommendations of the Study

Manufacturing firms should strengthen investments in green process innovation by modernizing production systems, expanding digital process monitoring, improving energy-efficient technologies, and redesigning operational routines to reduce waste and emissions. At the same time, firms should integrate these internal process improvements with green procurement practices, supplier environmental standards, cleaner material handling systems, and sustainable logistics coordination. Managers should therefore pursue process innovation as part of a broader supply chain environmental strategy so that environmental gains achieved within factory operations can be transmitted more effectively across the entire production and distribution network.

Theoretical Contribution

The findings further strengthen the Diffusion of Innovation Theory by demonstrating that the adoption of green innovations alone does not automatically translate into improved environmental sustainability. Rather, the environmental benefits of innovation are realized when green process innovations are effectively integrated with organizational capabilities and coordinated through green supply chain management practices. The study therefore extends the theory by showing that the diffusion of innovation should be viewed not merely as the adoption of new technologies or processes, but as the organizational integration of innovations across procurement, production, and logistics functions to generate sustainable environmental outcomes. This contribution advances the theoretical understanding of innovation diffusion by highlighting the complementary role of organizational and supply chain capabilities in transforming innovation adoption into measurable environmental sustainability performance.

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